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Renewable energy solutions for building cooling, heating and power system installed in an institutional building: Case study in southern Spain

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ABSTRACT

In the last few years the solar-assisted air-conditioning systems have been in intensive development and are considered as the viable application for the thermal solar systems more often, especially in regions of southern Europe. This is driven by the increasing higher electrical consumption in many countries (especially in Spain) during the summer months due to expanding usage of cooling systems. Another important aspect to consider is that the traditional cooling systems require additional power consumption and studies have shown that the refrigerants used in those systems cause ozone layer depletion and greenhouse effect. This paper presents and compares different building cooling, heating and power systems (BCHP) based on renewable energy sources with the conventional BCHP system. The main goal here is to find a more favourable, design for Solar Energy Research Center (CIESOL) from environmental and energy management perspective. The further comparison versus the reference system (conventional BCHP) is made between the three possible technologies. Hence we investigate here the solar absorption BCHP system and two other solutions: solar geothermal electric compression BCHP and solar electric compression BCHP system. We used the primary energy and CO_2 savings, initial cost, operating cost, maintenance cost, avoided costs and payback period as key performance indicators (KPIs). The energy performance of solar-assisted BCHP systems has been assessed considering as a benchmark the entire energy infrastructure operating today in the CIESOL building situated on the Campus of the University of Almeria. The results of the comparison demonstrated that only the solar absorption BCHP system presents energy saving potential. During 1 year it uses 61% less primary energy than the conventional BCHP system and is technically and economically feasible. At the same time, we used solar resource, abundant in the Almería region, in an efficient way, making CIESOL building consumption less energy intensive and ensuring environmental protection.

Contents

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1. Introduction

Making the use of renewable and non-renewable energy sources efficient and enabling to curb the climate change is the greatest challenge facing most of the developed countries. In European Union nearly 40% of final energy demand is led by domestic consumption public and corporate premises. In domestic households for example, two thirds of this energy is used for space heating. Publicly occupied buildings represent as much as 12% of the European Union building estate. Therefore a stronger emphasis on the energy efficiency issues in the public sector is crucial. Technically, “energy efficiency” means using less energy inputs while maintaining an equivalent level of activity. Often this term is interchangeably used with “energy savings” which is a broader concept that also includes consumption reduction through change in consumer choices. Unfortunately, a large energy savings potential remains untapped. There are number of techniques to halve the energy consumption in a building sector, but the uptake of the efficient strategies is too low. The barriers in building energy efficiency need to be overcome. Bearing in mind the above challenges, European Union has set itself a target of saving 20% of its primary energy consumption before 2020, this being a key step towards achieving long-term energy and climate goals [1]. As a result, in recent years in Spain an increased awareness of energy savings-related issues, such as control of greenhouse gases emissions into the atmosphere and environment degradation, has been raised. In response to that awareness campaign, Spanish government deployed the integration of solar energy use in buildings, using active solutions. It applied passive solutions such as building orientation, natural ventilation, daylighting strategy or thermal facade as well. As a consequence, a new energy efficiency policy called the Technical Building Code (CTE) was launched. The fundamental goal of CTE is to achieve a rational use of energy for buildings, reducing consumption, and leading to a wider use of the solar energy sources. Therefore, the main reason to apply renewable energy in residential sector is to reduce the consumption of conventional energy sources (i.e., fossil fuels and electricity) and to replace the inefficient systems with those that have a lower environmental impact. Hence, energy performance is a key issue when designing sustainable power and air-conditioning systems. Of course, economical parameters are equally important and a combined analysis of energy and sustainable performance can help to select the configuration which leads to the highest energy savings for a given investment [2].

In the last few years the solar-assisted air-conditioning systems have been in intensive development and are considered as the viable application for the thermal solar systems more often [3–5], especially in regions of southern Europe. This is driven by the increasing higher electrical consumption in many countries (especially in Spain) during the summer months due to expanding usage of cooling systems. There had been several studies on the performance of the energy systems designed for different building types and climates [6–19] mainly based on simulated data, however very little work has been conducted for real data of an existing operating office building with some many different energy systems that supply cooling, heating and electricity to its indoor space [20,21]. Hence the main purpose of this study is to audit the primary energy, money savings and environmental rewards produced by the energy retrofit of the typical office building located in southern Spain. We attempt to demonstrate the benefits of different solar-assisted hybrid BCHP systems, such as solar absorption, solar geothermal electric compression or solar electric compression in contrast with the advantages of using the conventional BCHP system, by benchmarking entire energy infrastructure operating today in the CIESOL building. This study provides engineers with a case study to compare another similar BCHP system. Hopefully research outputs from this paper will serve as inputs to future researches and development of activities and guidelines for solar-assisted BCHP systems' service design.

The first part of the paper focuses on a description of the Solar Energy Research Center and its actual energy infrastructure. Second, we carry out the study examining the energy demand of the building and all cooling and heating systems actually operating. Finally, we propose the comparative study of three different solar-assisted hybrid BCHP systems versus the conventional BCHP system.

2. CIESOL building description

2.1. Overview

Since the renewable energy solution mainly based on solar application will be considered for further reduction of energy consumption in the CIESOL building, it is fundamental to know about the meteorological conditions of Almería and especially the annual incidental radiation profile. Being aware of how much power is consumed, and of the real heating and cooling demand in the CIESOL building and what is the actual electricity infrastructure is crucial, since it allows to correctly size the proposed systems designs. Therefore, the behaviour and performance of the CIESOL building and its actual electricity infrastructure have been continuously monitored since 2006 by a data-acquisition system. The experimental data used in this work was collected

Nomenclature

T_{amb}	ambient air temperature (°C)
C_p	specific heat capacity of water (4.18 kJ kg^{-1} K^{-1})
$\dot{E}_C$	useful collectors' array energy (kWh)
$\dot{E}_{Aux}$	heat from auxiliary heater (kWh)
$\dot{Q}_E$	electricity demand (kWh)
$\dot{Q}_C$	cooling demand (kWh)
$\dot{Q}_H$	heating demand (kWh)
S9	entering auxiliary heater's temperature (°C)
S10	leaving auxiliary heater's temperature (°C)
S39	entering fan-coils' temperature (°C)
S41	building's return temperature (°C)
T_{out}	leaving flat-plate collectors' temperature (°C)
T_{in}	entering flat-plate collectors' temperature (°C)
$\dot{m}_c$	collectors' mass flow rate (m^3*h^{-1})
$\dot{m}_{Aux}$	auxiliary heater's mass flow rate (m^3*h^{-1})
$\dot{m}_B$	building's mass flow rate (m^3*h^{-1})
V_{OC}	open circuit voltage (V)
I_{SC}	short circuit current (A)
E_{PE}	annual primary energy consumption (MWh/y)
$E_{PE,reference}$	annual primary energy consumption of the reference system (MWh/y)
$E_{PE,renewable}$	annual primary energy consumption of renewable system (MWh/y)
$E_{PE,save}$	annual primary energy savings (MWh/y)
$E_{PE,save,rel}$	relative primary energy savings (MWh/y)
E_{elec}	total electricity consumption of studied system (MWh/y)
ε_{fossil}	the primary energy conversion factor of the fossil fuel used for the auxiliary heater
ε_{elec}	the primary energy conversion factor for the electricity production
$\Delta C_{oper,annual,renewable}$	annual cost saving of renewable system (€/year)
$C_{oper,annual,renewable}$	annual operation and maintenance cost of the renewable system (€/year)
$C_{oper,annual,ref}$	annual operation and maintenance cost of the reference system (€/year)
$\tau_{payback}$	payback time (years)
$C_{invest,tot,renewable}$	total investment cost of the renewable system (€)
$C_{invest,tot,ref}$	total investment cost of the reference system (€)
BCHP	building cooling, heating and power system
ABS	absorption chiller
COT	cooling tower
STC	cold storage tank
STH	heat storage tank
COL	flat-plate collectors
PV	photovoltaic panels
GHP	ground-source heat pump
HGHE	horizontal ground heat exchanger
HVAC	heating, ventilation and air conditioning
LiBr	lithium bromide

during 2011 with 1 min sampling period. The following subsections describe the above seasonal data and its usage for improving the design of energy solutions for CIESOL building and reducing its energy consumption.

2.2. Meteorological data

The Solar Energy Research Center (CIESOL) is situated in the Campus of University of Almería, a region in the southern Spain with the Mediterranean climate (c.f. Fig. 1). Based on the typical meteorological year data we know that the climate of Almería is moderate in winter and warm in summer with average top temperatures of 20 °C from June until September. The minimums present high values in every month of the year, especially in July and August, when they exceed 20 °C. Almería presents average annual global, diffuse, and direct normal radiation levels of 1805, 527, and 1977 kWh m^{-2}. The hottest month in this region is August, while the coldest one is January. Fig. 2(a) presents the monthly average ambient temperature measured during 2011, which is the experimental year adopted throughout this study. It shows the considerable increase of the ambient temperature between May and October, therefore we can assume that during this period the cooling system would probably operate at full-load conditions. From November to March the heating system works as normal, meanwhile during April and final days of October maintenance operations are carried out as there is no building demand. The similar pattern can be observed for the solar irradiation. Fig. 2(b) presents monthly solar irradiation on titled surface with the latitude angle for Almería during 2011. The highest values of solar radiation were registered between June and October. Bearing in mind the above considerations, and the fact that Almería has the advantage of some of the highest number of sun hours in Europe with more than 3000 hours annually, we outline the possibility to apply solar strategies in CIESOL building to reduce the conventional energy consumption and bring it closer to zero net definition building. According to the definition of "Net Zero Energy Building (NZEB)", specified by D.O.E. [6,22], a site zero energy building (ZEB) produces at least as much energy as it consumes in a year. The main goal of this study is to design the solar-assisted hybrid BCHP system for CIESOL building able to meet such criteria.

2.3. Building description

This building was built with bioclimatic standards and its design aimed at the efficient energy use. The single-storey building comprises an area of 1100 m^2 with 10 laboratories, 5 offices and one conference room. Approximately 45 employees work here and the maximum occupancy could be higher than 75 people including the conference room. The nave, entrance hall and all corridors are not equipped with cooling service, thus only 389 m^2 of the building surface are cooled. Fig. 3 presents the view of four sides of CIESOL building and Fig. 4 shows the ground and the first

Fig. 1. Map of Spain with Almería.

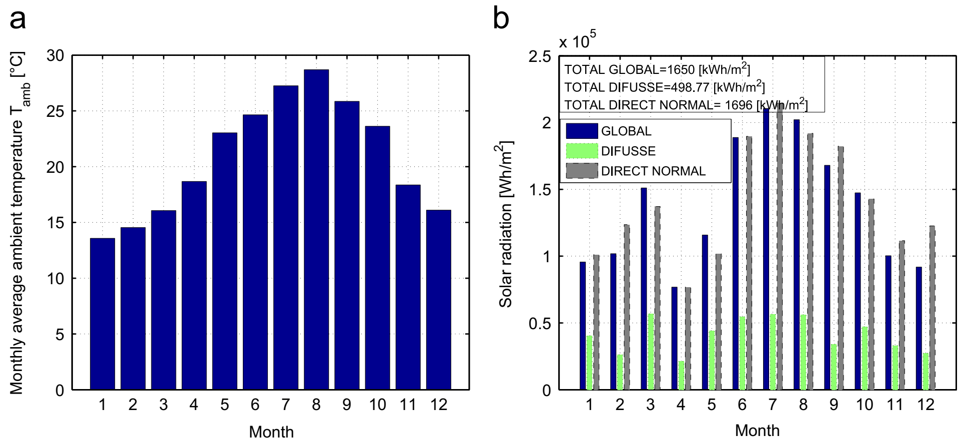

Fig. 2. (a) Monthly average temperature for Almería during 2011 and (b) monthly solar irradiation on titled surface for Almería during 2011.

Fig. 3. (a) View of CIESOL building with 160 m^2 flat-plate solar collectors' array, (b) the general view of CIESOL building, (c) east facade, and (d) north-west facade.

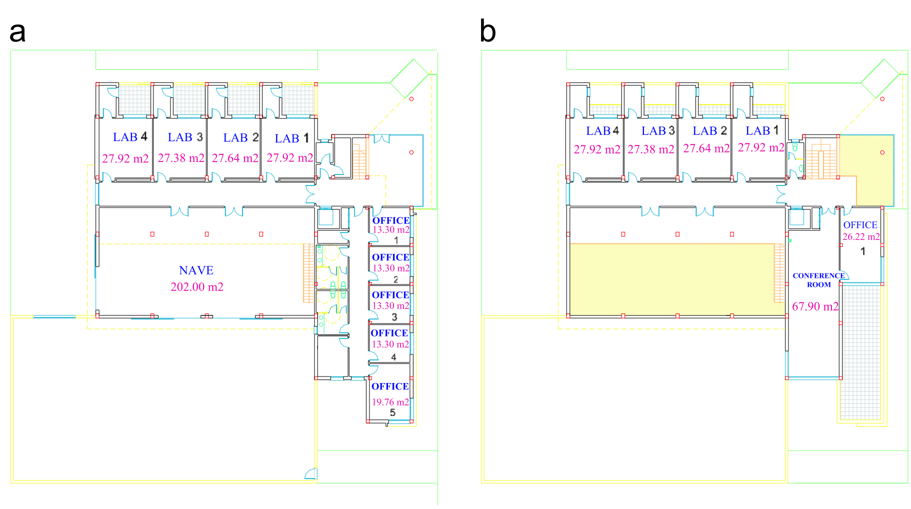

Fig. 4. (a) CIESOL ground floor plan and (b) CIESOL first floor plan.

floor plan of the CIESOL building. Basic data of the CIESOL building and each space load are summarised in Table 1.

3. Actual energy infrastructure

Today, CIESOL building is supplied by University of Almería campus' electricity grid. At the same time the grid-connected photovoltaic electricity production system (PV) provides electricity that is directly injected to the campus' grid. The heating and cooling demand is covered by solar-assisted air-conditioning system that has been working since October 2006. In order to ensure good thermal comfort inside the building, in the event of failure of the solar-assisted air-conditioning system, a conventional HVAC system, consisting of Ciatesa Hidropack WE 360 heat pump was installed. Additionally, to cover the heating and cooling demand in the nave of the building, we installed another air-conditioning system, that consists of ground-source heat pump (GHP), supplied by horizontal loop buried in the Campus' garden. Fig. 5 illustrates schematic diagram of electric and HVAC systems actually installed in CIESOL building. Below, we are going to present all systems applied in CIESOL building. Results obtained from analysis of those systems will serve to create different hybrid systems and finally to indicate the best configuration of cooling, heating and power system for CIESOL building. We attempt to find the most sustainable solution for our building, that would be able to cover all its electricity and air-conditioning demand and on the other hand would be characterised by its environmental sustainability.

Table 1
Basic data of the CIESOL building and each space load.

Room	Floor area (m^2)	Volume (m^3)	Maximum number of persons	Total required fresh air rate (ls^{-1})
Ground floor				
Laboratory 1	27.92	91.3	4	0.88
Laboratory 2	27.38	89.5	4	0.88
Laboratory 3	27.64	90.4	4	0.88
Laboratory 4	27.92	91.3	4	0.88
Office 1	13.3	43.5	2	0.22
Office 2	13.3	43.5	2	0.22
Office 3	13.3	43.5	2	0.22
Office 4	13.3	43.5	2	0.22
Office 5	19.76	64.6	3	0.48
First floor				
Laboratory 1	27.92	91.3	4	0.88
Laboratory 2	27.38	89.5	4	0.88
Laboratory 3	27.64	90.4	4	0.88
Laboratory 4	27.92	91.3	4	0.88
Office 1	26.62	87.1	2	0.42
Seminar room	67.5	220.7	30	15.6
Total	**388.8**	**1271.4**	**75**	**24.42**

3.1. Photovoltaic system

The CIESOL building has a photovoltaic electricity production system (PV) installed on its roof. The photovoltaic installation has a capacity of 9.324 kWp and has been in operation since 2008. It mainly consists of the photovoltaic modules, inverters and other electric equipment. The photovoltaic modules used are manufactured by the Spanish company Atersa. The model used is A-222P, with 60 polycrystalline cells and a power of 222 Wp. The overall number of modules is 42. The PV modules are arranged in 3 series strings, with 14 modules in each. The final DC/AC conversion of the electricity produced is carried out by means of three CICLO-3000 inverters. The inverters are tied to the national grid, due to obligatory legislation for utilization of renewable energy sources in Spain. The PV system is mounted on a stainless steel support structure facing south and titled at 22°. Such a tilt angle was chosen to maximise yearly energy production [23].

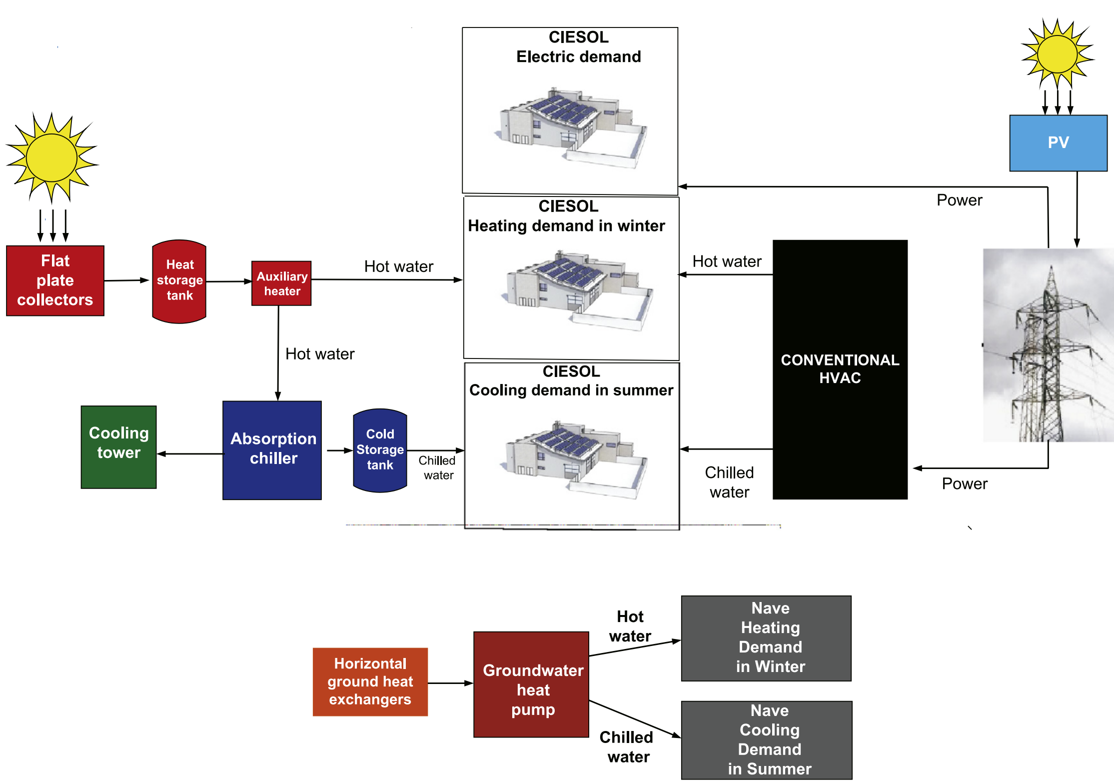

Fig. 5. Schematic diagram of electric and HVAC systems actually installed in CIESOL building.

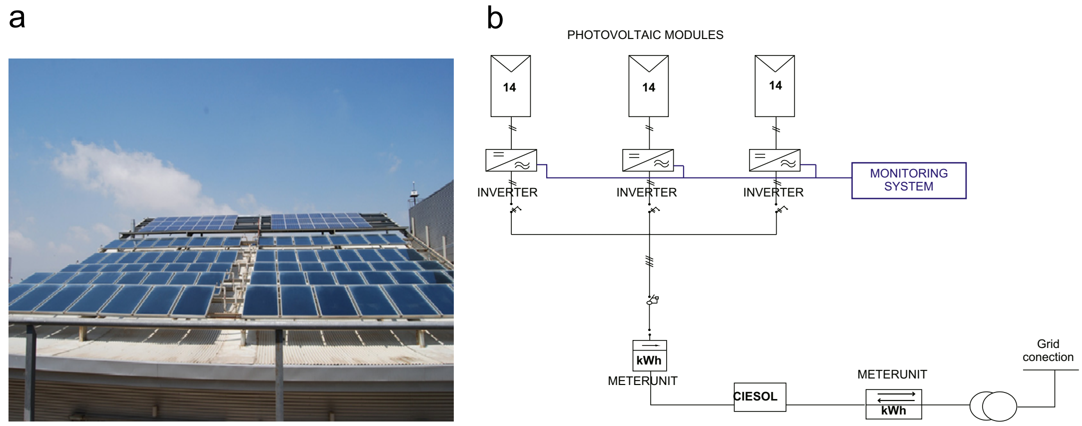

Fig. 6. (a) The photovoltaic and flat-plate collectors' arrays installed on the CIESOL building roof and (b) schematic diagram of the photovoltaic system.

Table 2
Operational data of A-222P.

Module data	A-222P
Maximum power (P_{max})	222 (W)
Open circuit voltage (V_{oc})	37.20 (V)
Short circuit current (I_{sc})	7.96 (A)
Number of solar cells	60
Area	1.628 (m^2)

Fig. 6(a) presents the 69 m^2 photovoltaic array installed in the CIESOL building and Fig. 6(b) shows schematic diagram of the photovoltaic system. According to the manufacturer data, we present in Table 2 the operational parameters of A-222P.

The performance of the photovoltaic system has been monitored by data-acquisition system since 2008. The experimental data used during this study was collected during 2011 with 1 min simple period. By using this data we calculated the annual amount of electrical energy generated by the photovoltaic system. Considering daily energy production for all inverters, we calculated the amount of potential electrical energy generation values for different months, integrating the area under the curve of the "power vs time" plots. For this purpose, all the power output results at the corresponding times of the day were input to MATLAB. By making use of the "sum" function found in MATLAB Library, numerical integration of these plots over time (i.e. the areas under the curves) was conducted. Applying the following equation:

$$Energy = Power \times Time \tag{1}$$

we will obtain the resultant numerical value, that gives the energy generation over a day in Wh [10]. Fig. 7 presents the daily average energy generation measured during 2011. It shows the considerable increase of the energy generation between April and September, reaching its highest value of 52 kWh in July. The total monthly energy generation potential registered during 2011 is presented in Table 3, with the total annual energy generation value of the order of 13.07 MWh, ranging from 822.5 in January to 1457 kWh in July, respectively. As can be seen the highest values were observed between June and August. It has to be outlined that during April and May we registered lower values of the total energy generation comparing to value from March. It was mainly due to the fact that during those 2 months we disposed of less quality acquired data than for other months.

3.2. Solar-assisted air-conditioning system

The solar-assisted air-conditioning system assessed in this study actually covers the annual CIESOL building's cooling demand during 5 months (from May to September) and its heating load from November to March. It always provides comfortable indoor conditions of the order of 25 °C and 22 °C during the cooling and heating period, respectively. Since no air-conditioning is required habitually in October and April the maintenance operations are usually carried out at that time.

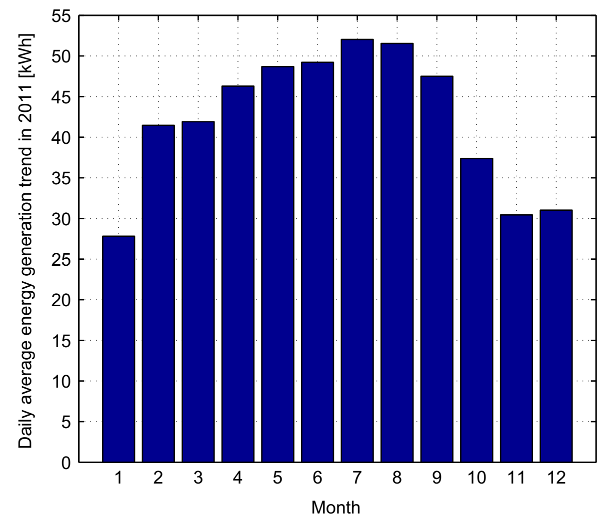

Fig. 7. Daily average energy generation trend registered in CIESOL building during 2011.

Table 3
Monthly energy generation for photovoltaic electricity production system installed in CIESOL building during 2011.

Month	**Monthly energy generation** (kWh)
January	822.5
February	903.4
March	1218.1
April	942.2
May	908.4
June	1241.8
July	1457.0
August	1426.5
September	980.0
October	1049.6
November	749.8
December	770.6
Total energy generation	**13,070.0**

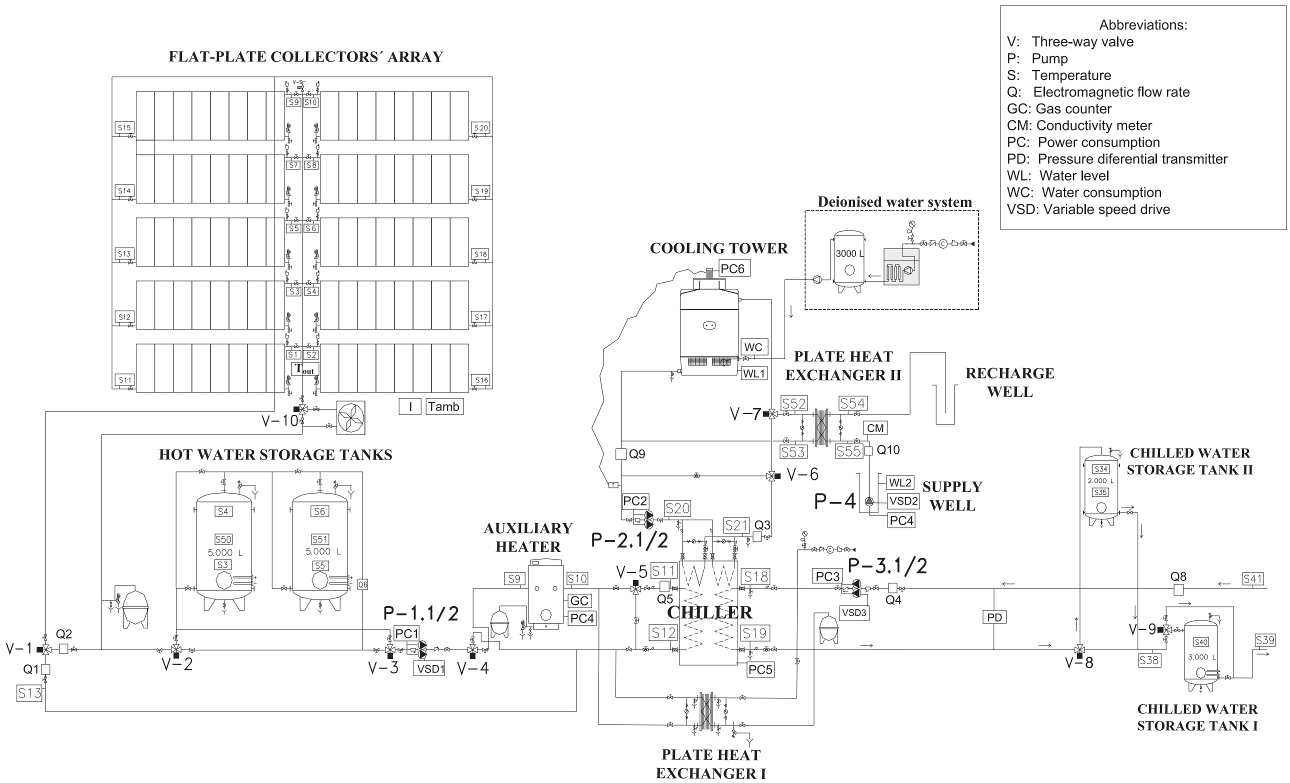

Fig. 8. The general scheme and measurement sensors of the solar-assisted air-conditioning system.

Fig. 9. Hot water storage tanks.

Fig. 8 illustrates a general scheme and measurement sensors of a solar-assisted air-conditioning system. The system employs a flat-plate collectors' array, the single-effect LiBr-H_2O absorption chiller, the cooling tower, groundwater cooling system, two hot storage tanks, the auxiliary heater, two chilled water storage tanks and the necessary peripheral equipment, such as valves and pumps. Analysis of the above system and its various operation modes has been recently presented [24–29]. In the following subsections the detailed description of the most relevant solar system's components will be presented.

- *Flat-plate collectors' array*: Having an aperture area of 2.02 m^2, the collector Solaris CP1 is used as the heat source, that is high-performance, single-glazed, selective absorption coated flat-plate collector. The solar collector medium is water without any additives, due to the favourable conditions of Almería. The collectors' array (160 m^2) is divided into 10 rows, each row having 8 collector units, facing south and tilted at an angle of 30° to the horizontal line. Fig. 6(a) presents the view of the collectors' array installed on the CIESOL building roof.
- *Hot water tanks*: Pursuing the goal of providing energy when the energy obtained from flat-plate collectors' array is insufficient, two storage tanks with a capacity of 5000 l each were introduced. Energy can be charged, stored and discharged daily or weekly depending on the control strategy. In the morning and afternoon, when the solar water is not sufficient to cover the cooling/heating demand, the system is fed by water provided from the hot storage tanks. Fig. 9 shows the image of both hot water storage tanks.
- *Auxiliary heat source*: As a backup of the solar energy heat source, an auxiliary heater with a heating capacity of 100 kW was mounted. The auxiliary heater is connected in series between the second storage tank and the absorption chiller/heat plate exchanger I. The mentioned heater may be used to boost the temperature of the hot water storage tanks if the leaving collectors' array temperature does not cover the heating or cooling requirements. It also can be used to cover the entire demand of the cooling/heating, whenever the storage heat is too low to be useful [30,31].
- *Plate heat exchanger*: The CIPRIANI Scambiatori heat plate exchangers were installed in the solar-assisted air-conditioning system. Plate heat exchanger I (cf. Fig. 8) with the capacity of the order of 100 kW was applied to cover the building's heating demand. In this mode the pump P1 circulates the hot water from solar collectors, hot storage tanks or auxiliary heater to heat exchanger. In plate heat exchanger returns building water, increasing its temperature to 45 °C, which is the building's water supply temperature during the winter season.
- *Absorption chiller*: In this work we tested the WFC SC 20 hot-water driven single-effect LiBr-H_2O absorption chiller manufactured by YAZAKI company with a rated capacity of 70 kW (cf. Fig. 10(a)). The chiller has a generator inlet temperature range of 70 °C to 95 °C, a cooling water inlet temperature range

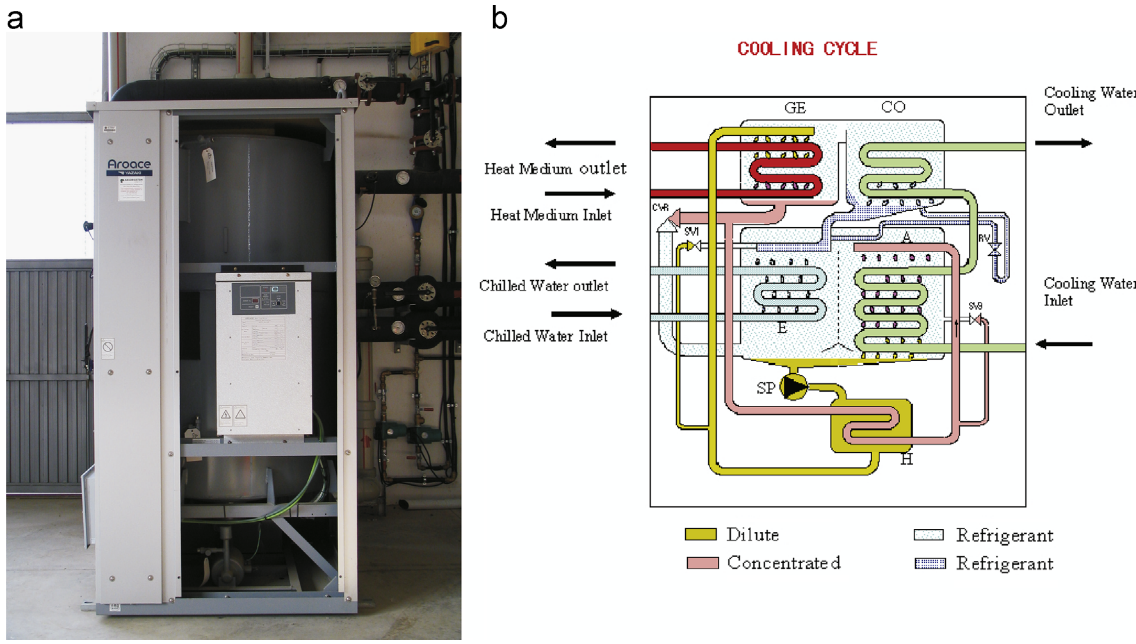

Fig. 10. (a) Absorption chiller installed in the CIESOL building and (b) a schematic drawing of an absorption cycle applied in the Yazaki chiller.

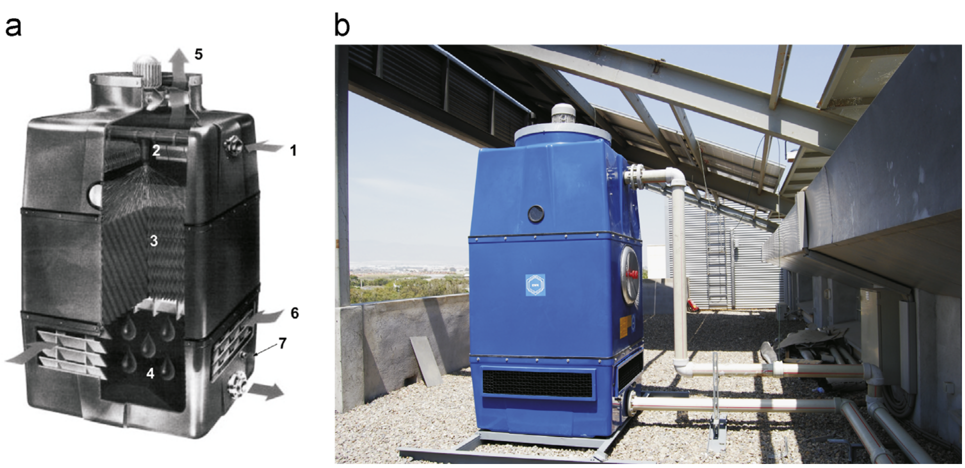

Fig. 11. (a) Schematic drawing of a cooling tower, picture from Sulzer Manual and (b) cooling tower installed in the CIESOL building.

of 24 °C–31 °C, and reaches its capacity of 70 kW under the following conditions [31]:

- Generator inlet temperature—88 °C (heat source flow rate: 4,8 ls^{-1}).
- Cooling water inlet temperature—31 °C (cooling water flow rate: 10,2 ls^{-1}).
- Chilled water outlet temperature—7 °C (chilled water flow rate: 3,06 ls^{-1}).

Referring to the schematic of the cooling cycle as shown in Fig. 10(b), lithium bromide solution (Dilute Solution) is pumped to the generator (GE) by the solution pump (SP) where it is heated to boiling point by the circulating heat medium. Refrigerant vapour (water vapour) is liberated from solution and flows to the condenser (CO) where it is condensed to a liquid state by rejection of heat to the cooling water circulating through the condenser coil. Because partial separation of the lithium bromide and the water in solution has occurred in the process of boiling in the (GE), an increase in concentration takes place and the resultant solution is termed (Concentrate Solution). Accordingly, the concentrate solution flows from (GE) to the heat exchanger (H), imparting heat to the dilute solution, before arriving at the absorber (A) to flow over the surface of the absorber coil. Concentrate solution cannot flow through the changeover valve (CVR) to the (A)/(E) area because the valve is closed for cooling function. Since cooling water is circulating through the absorber coil, a comparatively low vapour pressure is created due to the concentration of the lithium solution, and this is the environment which refrigerant liquid from the condenser encounters as it flows over the coil in the evaporator (E). The concentrate solution absorbs refrigerant vapor from the evaporator as the liquid refrigerant changes phase deriving heat of vaporization from the chilled water circulating through the evaporator coil. This results in the production of chilled water. The concentrate solution returns to a diluted state as refrigerant vapour is absorbed. In its relatively cool condition, it is collected in the (A)/(E) sump

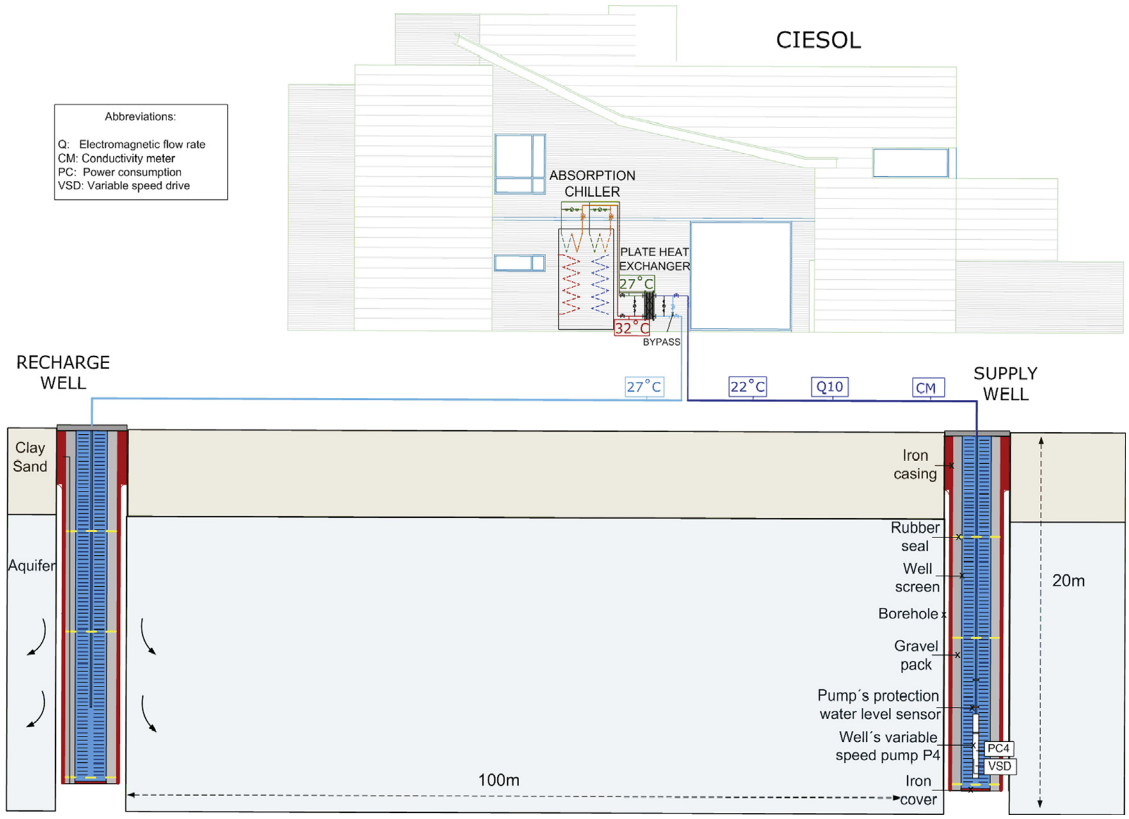

Fig. 12. Scheme of the shallow geothermal heat dissipation system.

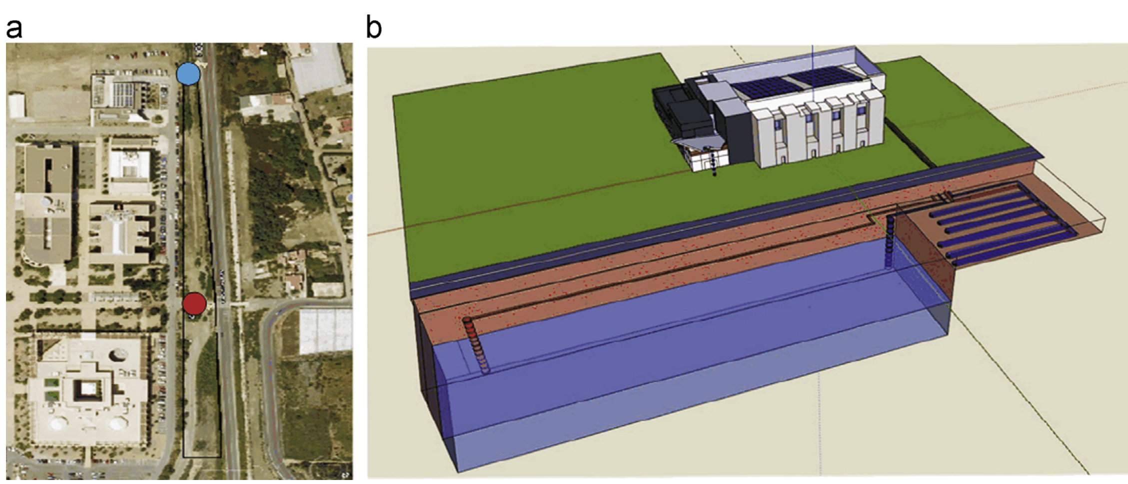

Fig. 13. (a) Position of supply and recharge well at the University Campus and (b) CIESOL and groundwater system's 3D model.

and there after forced by (SP) through the (H) collecting heat from the concentrate solution before returning to the (GE) for boiling again to repeat the cycle [32].

- *Cooling tower*: A cooling tower model SULZER EWK 100 with the cooling capacity of 170 kW was used for rejecting the heat of absorption and condensation, and supplying cooling water to the absorber and condenser in parallel at about 24 °C (cf. Fig. 11(a)). In a cooling tower air and water are in direct contact, therefore causing evaporation of a portion of water. In this case, the necessary heat to evaporate water is obtained from the cooling water circuit. By means of the distribution pipes (1) and the spray nozzles (2), located in the top of the tower, the return hot water is sprayed proportionally over the fill (3). The fill forms the heat exchange surface, making the water flow downwards through these channels (4). At the same time, and by means of the axial fan (5), air is sucked in from outside (6), and goes upward in the opposite direction to the water flow, creating its cooling. The flow of the evaporated water is compensated by the addition of fresh water (7)proceeding from the deionised water system (cf. Fig. 8) [33]. Water used in the cooling water circuit may cause corrosion if not properly analysed and treated. The cooling tower circuit is particularly vulnerable because it is an open circuit, susceptible to scaling from precipitation of dissolved solids and to growth of algae and microorganisms in the water. Thus, appropriate continuous water treatment is essential for the correct operation of the absorption chiller. Otherwise, poor maintenance could result in extreme health hazards, such as a Legionella outbreak, and in a

diminished life span of the chiller [33]. Therefore, a deionised water system was applied to purify the water. It consists of a reverse osmosis system, model ARIUM 613, capable of providing 150 litres of high-quality water per hour. It is a very efficient and low-maintenance system. A storage tank with a capacity of 3000 litres and a distribution pump were integrated as well to provide permanent flow to the cooling tower, which is essential for its correct operation. When the cooling tower is used, the valve V14 is kept open and V6 is managed by internal absorption chiller control depending on the temperature found in the cooling circuit (cf. Fig. 8).

Fig. 11(b) shows a picture of the cooling tower applied in the solar-assisted air-conditioning system described in this work.

- *Shallow geothermal system*: Considering that using a cooling tower involves the risk of Legionella outbreak, the alternative heat dissipation method was tested. Since water has naturally higher heat transfer capability than rock, and because of the lack of adequate space for an underground heat exchanger, the shallow geothermal system was implemented. This system benefits from the fact that Almería region has natural groundwater resources.

  Fig. 12 presents scheme of the shallow geothermal open-loop system. The core idea of this groundwater heat dissipation system is to provide cooling water to absorption chiller. Two 20 m deep wells were drilled. The Pump P4 is a variable speed pump that can operate between 0 and 15.5 m^3h^{-1}, depending on the amount of the heat rejected. Groundwater is circulated from the aquifer at about 22 °C through the supply well and is forced through the heat exchanger II with capacity of 170 kW, where the heat is extracted (cf. Fig. 8). In the heat exchanger II, the groundwater increases its temperature due to heat rejection which is results from absorption and condensation. The water is then discharged back to the aquifer thorough the second well, that is situated about 100 m away from the supply well, to prevent hydraulic and thermal interferences [34,35]. Fig. 13(a) shows the location of both wells at the University Campus and (b) presents the 3D model of the CIESOL building and the groundwater cooling system. This system has an important advantage: it does not present any water consumption and does not need such rigorous maintenance comparing to the cooling tower's and for all that reasons was tested during 2011.
- *Chilled water system*: In aim to provide the cooling capacity when solar heat is insufficient, we installed two chilled water storage tanks with the capacity of 2000 l and 3000 l, respectively. Those storage tanks were connected between the absorption chiller and fan-coil units system. Fig. 14 illustrates the image of the chilled water storage tanks installed in the CIESOL building.
- *Fan-coils*: A fan-coil system is an air–water heat exchanger. That heat exchanger is supplied with hot or chilled water provided from the solar-assisted air-conditioning system. The fluid exchanges its energy in the fan-coil and the air (hot or cold) flows to heating or cooling space [2]. Four types of the fan-coil units were mounted due to the different cooling spaces (15 quarters), already introduced in the Section 2.3 of this work.

Fig. 14. Chilled water storage circuit.

Fig. 15 presents the chilled water distribution network with outdoor air supplied in the CIESOL ground floor plan. The outdoor air is transported to the fan-coil where is mixed with the re-circulated air and conditioned [36]. The unit can be used for either heating or cooling the indoor air, depending on the central system operation mode. In cooling mode, the fan-coil unit has the maximum and minimum inlet temperature of the order of 15 °C and 7 °C, respectively. Meanwhile, during the winter mode the water supply/return temperature is 45/40 °C.

The performance of the solar-assisted air-conditioning system has been monitored by data-acquisition system since 2006. The experimental data used in this study was collected during 2011 with 1 min simple period. Using this data, we calculated the monthly useful collectors' array energy ($\dot{E}_C$), energy produced by

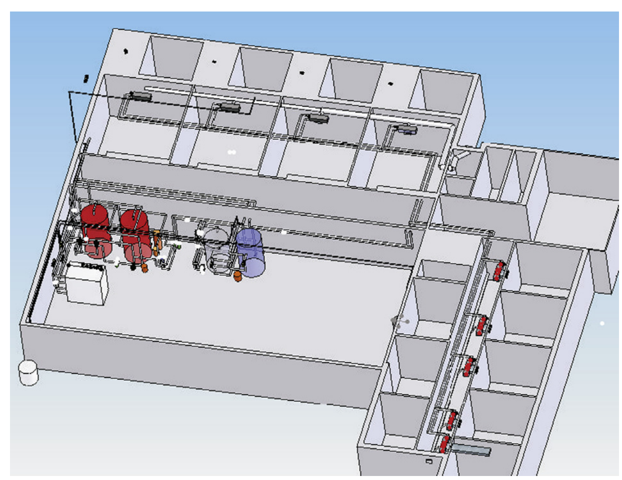

Fig. 15. The chilled water distribution network in the CIESOL ground floor plan. Scheme by Estrada Sánchez.

Table 4
Monthly trend of thermal energy produced by solar collectors, auxiliary heater, cooling and heating demands registered in solar-assisted air-conditioning system during 2011.

Month	$\dot{E}_C$ (kWh)	$\dot{E}_{Aux}$ (kWh)	$\dot{Q}_C$ (kWh)	$\dot{Q}_H$ (kWh)
January	4720.0	1086.0	0	3080.3
February	5950.0	558.6	0	2759.3
March	7170.0	128.1	0	2466.5
April	5370.0	0	0	51.23
May	6130.0	721.7	436.9	0
June	10,900.0	2880.0	3409.0	0
July	13,100.0	2374.0	4646.1	0
August	12,400.0	584.7	5066.0	0
September	11,000.0	153.5	621.1	0
October	6010.0	382.3	322.8	0
November	3950.0	58.6	0	102.1
December	3840.0	809.1	0	1846.0
Total energy generation	**90,540.0**	**9736.6**	**14,501.8**	**10,308.0**

the auxiliary heater ($\dot{E}_{Aux}$), cooling ($\dot{Q}_C$) and heating ($\dot{Q}_H$) production registered in the solar-assisted air-conditioning system during 2011 (cf. Table 4). The useful collectors' array energy ($\dot{E}_C$) can be expressed as

$$\dot{E}_C = \int_{t=0}^{t_x} ((T_{out} - T_{in}) \cdot C_p \cdot \dot{m}_C)\, dt \tag{2}$$

where T_{out} and T_{in} is the leaving and entering flat-plate collectors' temperature, $\dot{m}_C$ is the collectors' mass flow rate, C_p is the specific heat capacity of water and t_x is the daily collectors' array operation time.

The energy produced by the auxiliary heater ($\dot{E}_{Aux}$) was obtained using the following equation:

$$\dot{E}_{Aux} = \int_{t=0}^{t_x} ((S_{10} - S_9) \cdot C_p \cdot \dot{m}_{Aux})\, dt \tag{3}$$

where S_{10} and S_9 is the leaving and entering auxiliary heater's temperature, $\dot{m}_{Aux}$ is the auxiliary heater's mass flow rate and t_x is daily auxiliary heater's operation time.

The cooling ($\dot{Q}_C$) production was calculated as

$$\dot{Q}_C = \int_{t=0}^{t_x} ((S_{41} - S_{39}) \cdot C_p \cdot \dot{m}_B)\, dt \tag{4}$$

where S_{41} and S_{39} is the building's return temperature and entering fan-coils temperature, respectively, and $\dot{m}_B$ is the building's mass flow rate and t_x is daily solar-assisted air-conditioning system's operation time.

The heating ($\dot{Q}_H$) production can be presented as follows:

$$\dot{Q}_H = \int_{t=0}^{t_x} ((S_{39} - S_{41}) \cdot C_p \cdot \dot{m}_B)\, dt \tag{5}$$

As can be observed during studied year, the auxiliary heater's energy generation was of the order of 9.736 MWh, producing the annual gas consumption of the order of 229.5 m^3 (cf. Fig. 16(a)). One can see that the highest values of the energy produced by the auxiliary heater are during the summer season. It is mainly due to the fact that during this period we carried out many experiments to study the performance of the absorption chiller versus the generator's inlet temperature. Nevertheless, in this study we will consider the above consumption as the total annual gas

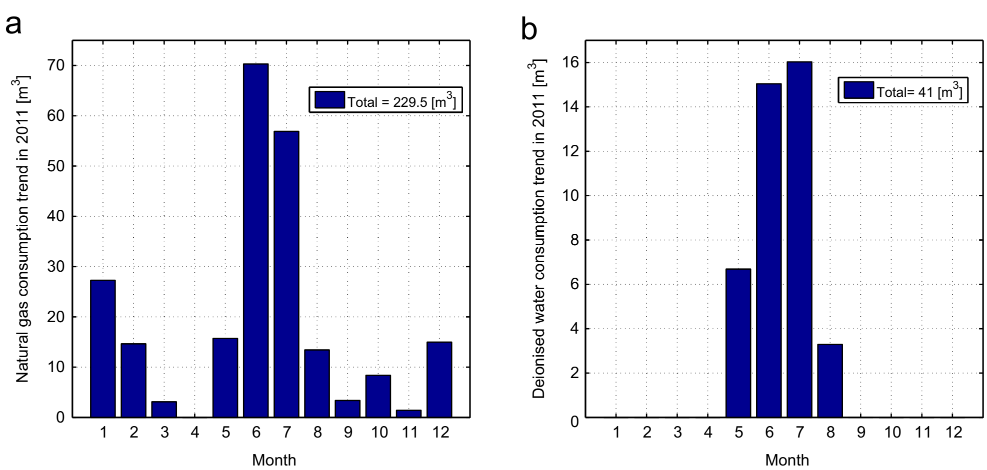

Fig. 16. (a) Natural gas consumption trend in 2011 and (b) deionised water consumption trend in 2011.

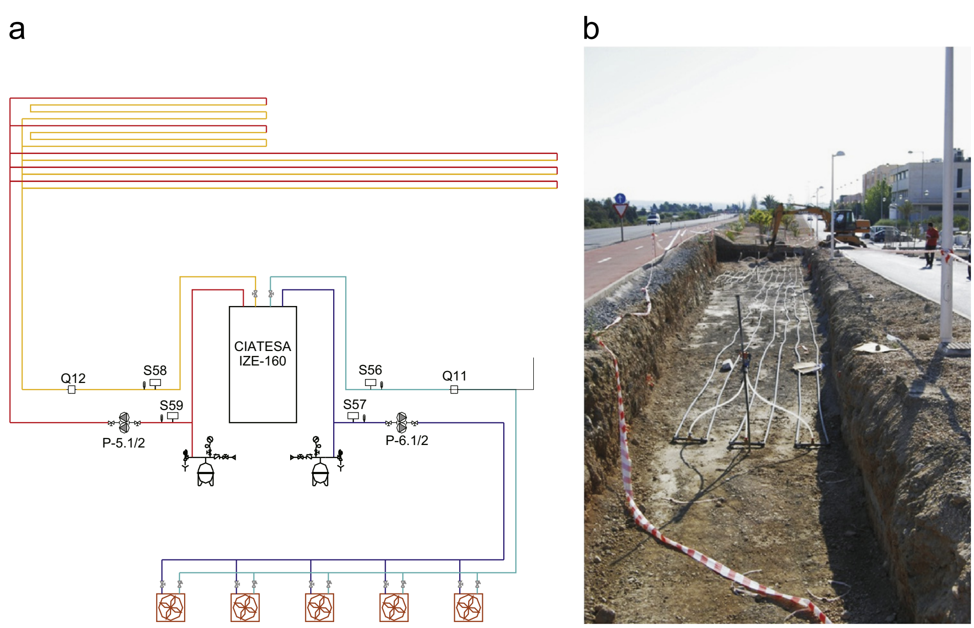

Fig. 17. (a) General scheme of the ground-source heat pump system installed in the nave of the Ciesol building and (b) horizontal loop heat exchanger.

consumption, since it is the real measurement output of our solar-assisted air-conditioning system. Fig. 16(b) illustrates the deionised water consumption in the cooling tower during summer of 2011. After the cooling period of 2011, we found that the total deionised water consumption was approximately 41 m^3. However, it needs to be highlighted that during that period we also used the shallow geothermal system, thus this consumption could be even higher if we apply the cooling tower as the unique heat dissipation system.

3.3. Ground-source heat pump system

As was already mentioned, to cover the cooling and heating demand in the nave of the building, we installed another air-conditioning system, that consists of ground-source heat pump (GHP). The heat exchangers are located in the underground of the University garden. This system consists of Ciatesa IZE-160 water–water compression heat pump, with a cooling and heating capacity of 30.6 kW and 38.5 kW (cf. Fig. 17(a)), respectively. Five, 1 m deep, horizontal loops with the total occupied area of the order of 185 m^2, were used as the horizontal, connected in parallel, heat exchanger (cf. Fig. 17(b)). Due to the favourable conditions of Almería, the heat carrier fluid, in this case water without any additives, is circulated through the pipes from which it extracts heat, or rejects heat to the surrounding ground during the winter and summer time. Five air–water heat exchangers (aeroterms) are supplied with hot or chilled water provided from the heat pump. In cooling mode, the aeroterms units have the maximum and minimum inlet temperature of the order of 15 °C and 7 °C, respectively. Meanwhile, during the winter mode the water supply/return temperature is 45/40 °C.

This kind of systems have several advantages like elimination of cooling tower, no water treatment is necessary, they do not require specific hydrogeologic conditions in the underground layers. This technology relies on the fact that, at depth, the Earth has a relatively constant temperature, warmer than the air in winter and cooler than the air in summer [37–43]. The compression heat pump operates on mechanical energy, driven by electricity. Considering electric power of the heat pump and all peripheral equipments, we obtained the total electric demand of the order of 28 kW.

3.4. Conventional HVAC system

As was already mentioned in order to ensure good thermal comfort inside the building in the event of failure of the solar-assisted air-conditioning system, we installed a conventional HVAC system, consisting of a Ciatesa Hidropack WE 360 air-water heat pump (cf. Fig. 18), with a cooling and heating capacity of 76.4 kW and 82.6 kW, respectively. The electric power of this equipment is 26 kW. It must be highlighted that the heat pump does not constitute a back-up but an alternative, independent system, which has been used only sporadically, since the solar-assisted air-conditioning system has been able to cover the heating and cooling demand of the building during the year. This system serves also as a test stand for different scientific researches focused on building's load simulation.

4. Energy consumption data

In the following subsections we emphasize the importance of sustainable power and air-conditioning system integration that would be able to provide the best energy performance to CIESOL building. To achieve this goal, an examination of energy demand of CIESOL building was conducted. Second, the energy demand of the solar-assisted air-conditioning system was examined in detail. Subsequently, the heat pump's energy demand was studied, and we applied it as another possible solution. Finally, the conventional system's power consumption was analysed, as we use it as our reference system.

Fig. 18. Conventional HVAC system installed in the CIESOL building.

4.1. Energy demand of CIESOL building

Since our purpose is to analyse CIESOL building as an office building, we highlight that during this study we consider only the energy consumption of facilities described in Table 1 and not of the entire building. In the following sections we use CIESOL building nomenclature as the office building, that consists of the above facilities (cf. Table 1). Additionally, we assume that we take into account only its daily values, since usual office hours are from 8 a.m to 9 p.m (6 a.m. to 7 p.m. of UTC time during the summer period and 7 a.m. to 6 p.m. of UTC time during the winter time). Figs. 19 and 20 demonstrate the daily energy consumption of areas located on the ground and first floor in the CIESOL building, for one experimental day (11/07/2011).

Considering daily energy consumption for all locations, we found the amount of electrical energy consumption values for different months mapping the area under the curve of the "power vs time" plots presented in Figs. 19 and 20, making use of Eq. (1) [10]. Fig. 21(a) illustrates the annual daily profile of energy consumption measured in all described areas of CIESOL building during 2011. As mentioned, we consider the energy consumed only during the office hours (from 8 a.m to 9 p.m). Adding up the daily values, we obtained the total electricity consumption during 2011, that was of the order of 25.9 MWh/year. After 2011 we also ascertained that the highest daily peak of CIESOL's energy consumption is of the order of 21.1 kW (cf. Fig. 21(b)). Both values are crucial to correct sizing of alternative power systems proposed for CIESOL building.

4.2. Energy demand of solar-assisted air-conditioning system

In this analysis, we consider all elements of solar-assisted air-conditioning system, that represent any electricity consumption, such as the absorption chiller, cooling tower, shallow geothermal

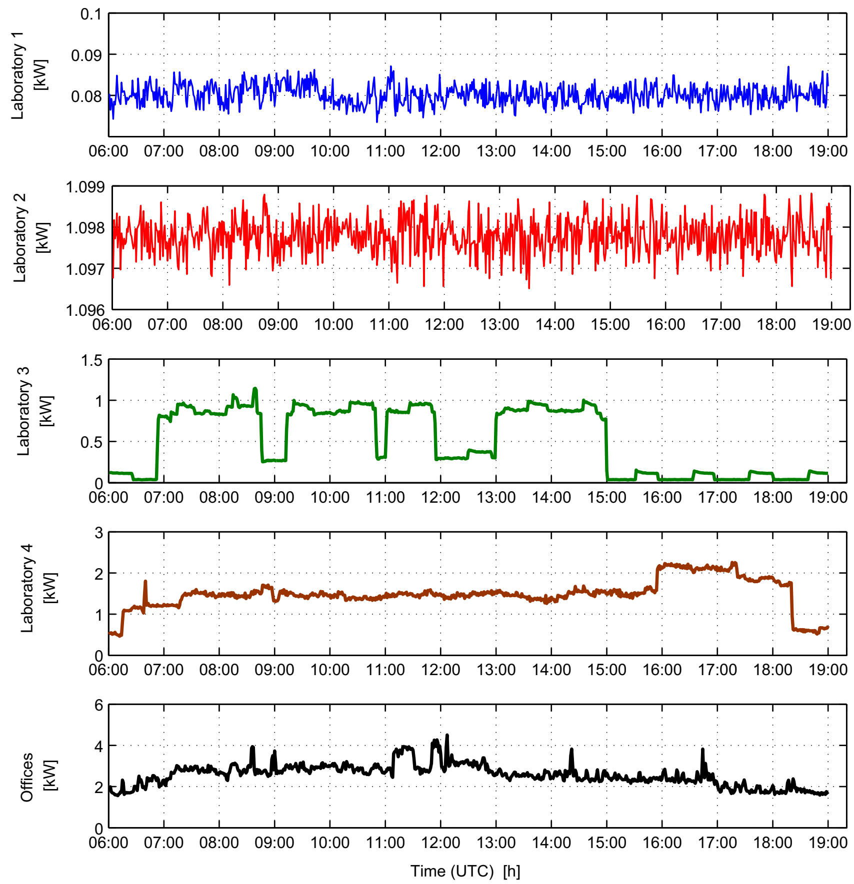

Fig. 19. Daily energy consumption in ground floor of CIESOL building for one experimental day (11/07/2011).

system, auxiliary heater and pumps P1, P2 and P3 (cf. Fig. 8). Again, making use of Eq. (1) we calculated the daily energy consumption in Wh for all solar-assisted air-conditioning system's equipments [10]. Fig. 22 presents the annual profile of energy usage of each of above equipments. As can be observed, the major annual consumption rise occurs for pumps P2, P3 and especially P1. The high energy consumption of pump P1 is resulting from its increased working hours, since its operation is strictly related to the flat-plate collectors array operation. To protect the flat-plate collectors against overheating, the control algorithm activates the P1 pump frequently. Fig. 23(a) illustrates the daily trend of energy expenditure registered in the solar-assisted air-conditioning system during 2011. It ought to be noted that above system works only during office hours, from 8 a.m. to 9 p.m. Adding up the daily values, we reached the total electricity consumption of the order of 7.985 MWh for 2011. Fig. 23(b) illustrates the daily peak of energy usage of the entire solar-assisted air-conditioning system during 2011. We deduced that, for that period, the highest measured value was of the order of 11.24 kW. Another important parameter to take into account, when deciding how the selected system should operate, is its annual operation time. Fig. 24 presents the daily solar-assisted air-conditioning system's operation time registered during 2011. One can discern that its mean value was of the order of 9 hours per day and its annual value was 2769 h. The correct sizing is crucial for designing the best solution for the air-conditioning systems that we attempt to propose in this work for CIESOL building.

4.3. Energy demand of heat pump system

Unfortunately, we have not the electricity consumption meter for the heat pump system. Nevertheless, considering the time of the total solar-assisted air-conditioning system registered in 2011, we can estimate that its readings could be of the order of 2769 h (cf. Fig. 24). As was already mentioned in paragraph 3.3, the electric power of this equipment and all peripheral equipments is of the order of 28 kW, therefore its annual power consumption could reach even 77.5 MWh.

4.4. Energy demand of conventional system

Neither in case of the heat pump system nor in this case have we had the electricity consumption meter for the conventional HVAC system. However, as in the earlier case, we can estimate it considering the time of the total solar-assisted air-conditioning system registered in 2011. It was of the order of 2769 h (cf. Fig. 24). As was already mentioned in Section 3.4 the electric power of this equipment is 26 kW, therefore its annual power consumption could reach as much as 72 MWh.

5. Performance parameters

The goal of this study is to compare the energy, economical and environmental performance of four alternatives for meeting power, air cooling and heating requirements of the CIESOL building. To compare the viability of the provided options we considered the annual energy cost, annual primary energy and CO_2 savings contributions generated by each of the proposed designs. Then we contrasted their parameters with those of the reference design, where all energy needs are met by the conventional system [11]. During this study we excluded fan-coils units, since

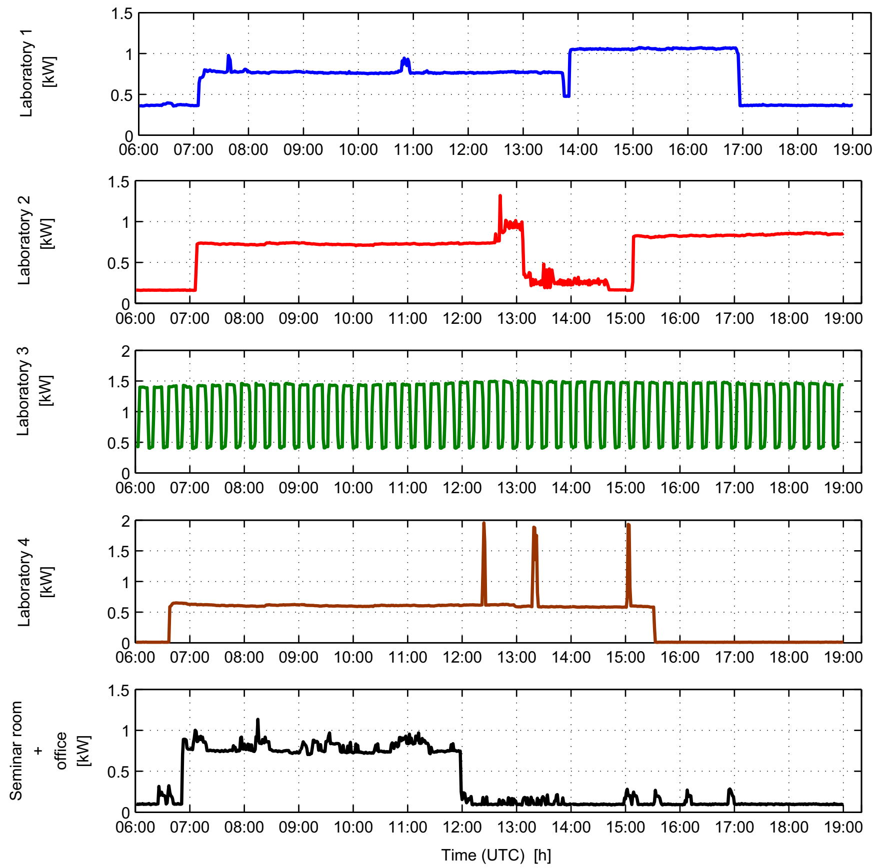

Fig. 20. Daily energy consumption in first floor of CIESOL building for one experimental day (11/07/2011).

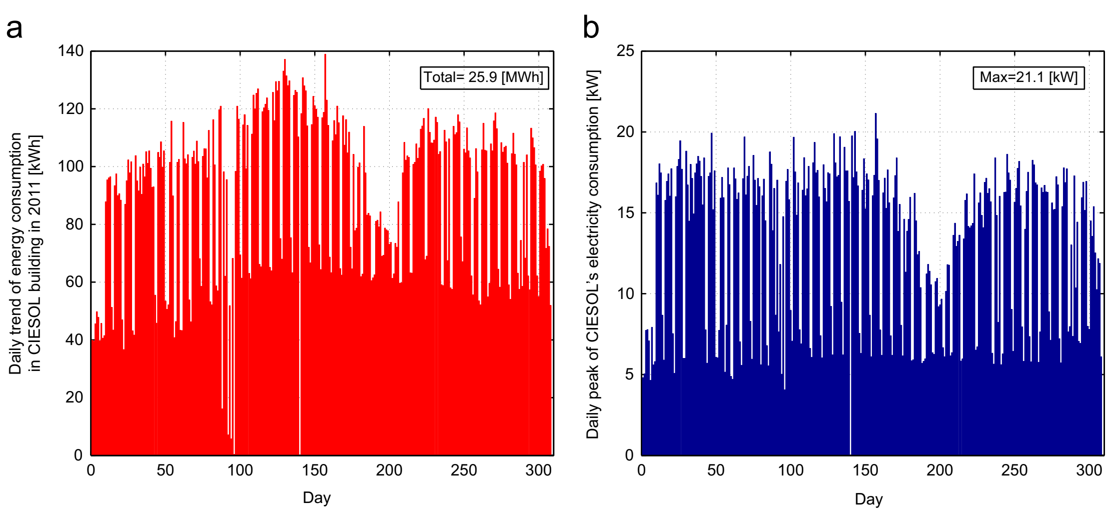

Fig. 21. (a) Annual profile of energy consumption in CIESOL building during 2011, (b) daily peak of energy consumption in CIESOL building during 2011.

operation of those elements is the same for all alternatives and they would not affect the final comparison.

5.1. Energy performance

The annual primary energy consumption, E_{PE} is defined as [2]

$$E_{PE} = \dot{E}_{Aux} \cdot \varepsilon_{fossil} + E_{elec} \cdot \varepsilon_{elec} \tag{6}$$

where $\dot{E}_{Aux}$ is the annual heat from auxiliary heater, ε_{fossil} is the primary energy conversion factor of the fossil fuel used for the back-up heat source (natural gas), E_{elec} is a total electricity consumption of the studied system (i.e., for electrically driven components, for example pumps) and ε_{elec} is the primary energy conversion factor for electricity production. In this study we used a primary energy conversion factor of 2.11 (MWh of electricity per MWh of primary energy) and a primary energy conversion factor for heat from natural gas of 1.07 (MWh of heat per MWh of primary energy) [2,44] (cf. Table 5).

The annual primary energy savings, $E_{PE,save}$, is given as

$$E_{PE,save} = E_{PE,reference} - E_{PE,renewable} \tag{7}$$

where $E_{PE,reference}$ is the annual primary energy consumption of the reference system and $E_{PE,renewable}$ is the annual primary energy consumption of the renewable system (i.e., solar driven system).

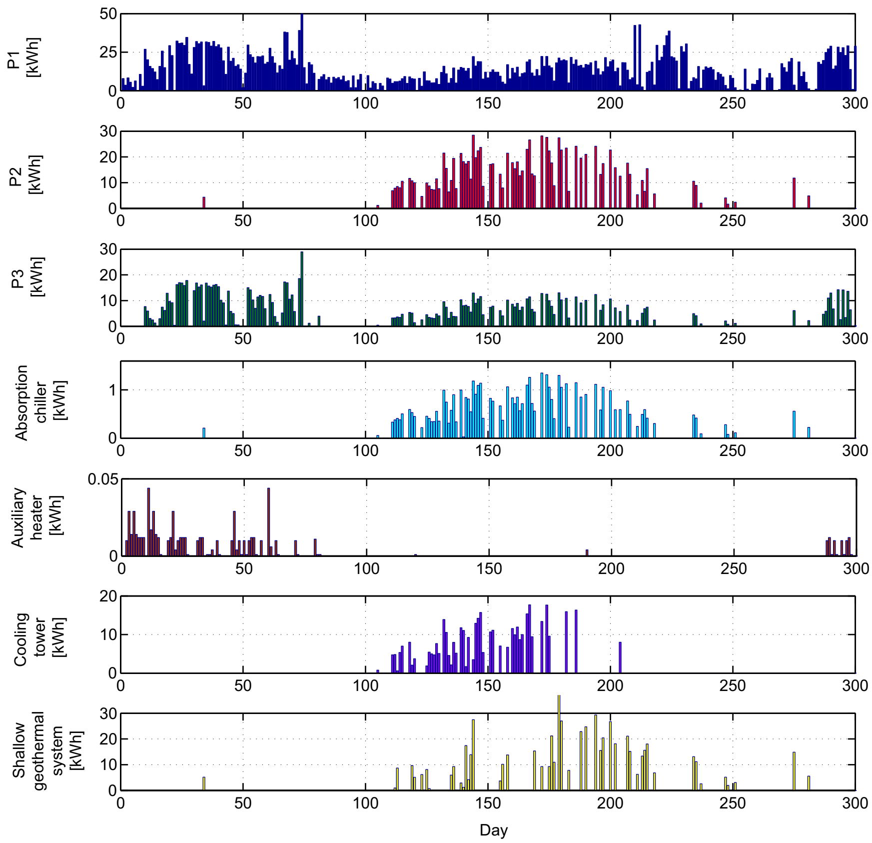

Fig. 22. Energy consumption of main solar-assisted air-conditioning system's components during 2011.

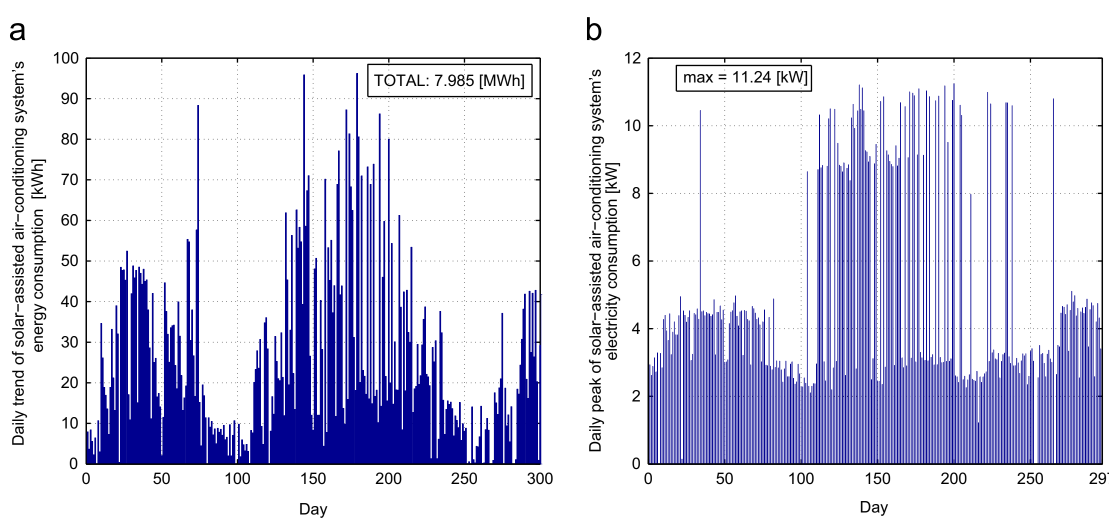

Fig. 23. (a) Daily trend of solar-assisted air-conditioning energy consumption during 2011 and (b) daily peak of solar-assisted air-conditioning system's energy consumption during 2011.

The relative primary energy savings $E_{PE,save,rel}$, are defined as [2]

$$E_{PE,save,rel} = E_{PE,save}/E_{PE,reference} \tag{8}$$

5.2. Economic performance

Another aspect, which has to be taken into account in reaching a good decision about the selection of any power and air-conditioning system, is the cost performance. Adding up all the investment (initial) cost for each component of the entire system we will obtain its total investment cost. Subsequently, it is necessary to calculate the annual costs of studied systems. To fulfill this goal we have to use the annual data of energy, water and natural gas consumption and some additional information, that was summarised in Table 5. The total annual cost is calculated by summing up the energy and water cost with maintenance cost. To evaluate the cost performance of proposed systems below we will introduce few basic concepts [2].

If the annual cost for operation and maintenance of the renewable energy is lower than for reference system due to

lower energy consumption and related cost, this cost saving, $C_{oper,annual,renewable}$, is given by

$$\Delta C_{oper,annual,renewable} = C_{oper,annual,renewable} - C_{oper,annul,ref} \quad (9)$$

where $C_{oper,annual,renewable}$ is the annual operation and maintenance cost for the renewable system variant and $C_{oper,annual,ref}$ is the annual operation and maintenance cost for the reference system.

Considering the above definition, we can estimate the payback time, $\tau_{payback}$, which can be applied to compare the cost performance of different renewable system designs. This parameter can be expressed as

$$\tau_{payback} = C_{invest,tot,renewable} - C_{invest,tot,ref} / \Delta C_{oper,annual,renewable} \quad (10)$$

where $C_{invest,tot,renewable}$ is the total investment cost for the solar system and $C_{invest,tot,ref}$ is the total investment cost for the reference system [2].

6. Comparative study of building cooling, heating and power systems' configurations

In this study we present conventional and alternative solar-assisted hybrid BCHP systems, configured to provide the same level of comfort and power generation in CIESOL building. The BCHP system should be designed with the capability to satisfy all demand variations. The expected annual demands are presented in Table 6. These data are the crucial information that we apply to infer the best solution for power and air-conditioning system design. Those demands are based on the actual annual data gathered for CIESOL building in 2011. Nevertheless, it needs to be emphasised that the final design should also have the capability to handle any additional demand changes. The cooling, heating and especially electricity demand should be always met without any restrictions. In the following subsections, we are going to present different energy systems to find the best one. Such system would be able to cover all CIESOL building's energy necessities, being at the same time the most economic and most environmental friendly [45,46]. First, we present three different solar-assisted hybrid BCHP systems and results obtained during the comparison of those systems versus the reference case. As the reference system we adopted the conventional HVAC system and grid connected power supply. The feasibility of each option will be assessed in terms of its primary energy savings, initial cost, operating cost, maintenance cost, avoided costs and payback period in two different scenarios. In Scenario 1 the produced energy is consumed internally in CIESOL building and no electricity is sold back to the grid. In Scenario 2 produced electricity is sold to the grid, meanwhile CIESOL's electricity demand is covered by external campus' grid. Investment and maintenance cost will be studied taking into account the data provided by manufacturers [12,13].

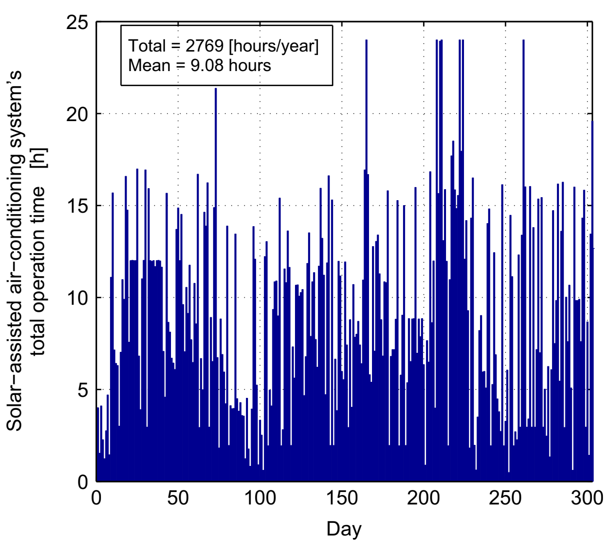

Fig. 24. Solar-assisted air-conditioning system's total operation time during 2011.

6.1. Energy system designs

6.1.1. Design 1: electric compression BCHP system (reference system)

In this design the building's cooling, heating and power are supplied by “conventional” systems. CIESOL's heating and cooling demands are met converting electricity from the campus' grid into thermal energy. In this case the conventional HVAC, already described in Section 3.4, is used to provide heating and cooling, whereas CIESOL's electric demand is covered directly from campus' grid. Fig. 25(a) presents the schematic diagram of Design 1. As was already described in Section 4.4, considering the total solar-assisted air-conditioning system's operation time of the order of 2769 h and the electric power of the conventional HVAC of the order of 26 kW, we can estimate HVAC's annual power consumption of the order of the order of 72 MWh. Since, the main objective is to find an optimal system to cover not only the air heating and cooling, but also the electricity demand, we need to consider

Table 6
Summary of the utility demands registered in CIESOL building during 2011.

Utility demand	Maximum (kW)	Mean (kW)	Minimum (kW)	Total (MWh)
Electricity (Q_E)	21.10	10.70	4.80	25.90
Cooling ($\dot{Q}_C$)	154.00	70.00	43.00	14.50
Heating ($\dot{Q}_H$)	163.80	18.00	18.0	10.31

Table 5
Parameters used for the economic performance of the studied designs.

Cost type	Cost element	Unit	
Energy and water cost	Electricity costs	(€/MWh)	142.3
	Natural gas costs	(€/MWh)	36.0
	Water costs	(€/m^3)	28.0
Maintenance	Annual maintenance cost of system	(% of investment)	1.0
Self-energy production	Photovoltaic electricity costs	(€/MWh)	320.0
Parameters related to environmental performance	Conversion factor for electricity, MWh electricity per MWh primary energy		2.11
	Conversion factor for natural gas, MWh natural gas per MWh primary energy		1.07
	CO_2 emission from electricity generation	(g/kWh)	250
	CO_2 emission from natural gas	(g/kWh)	201.7

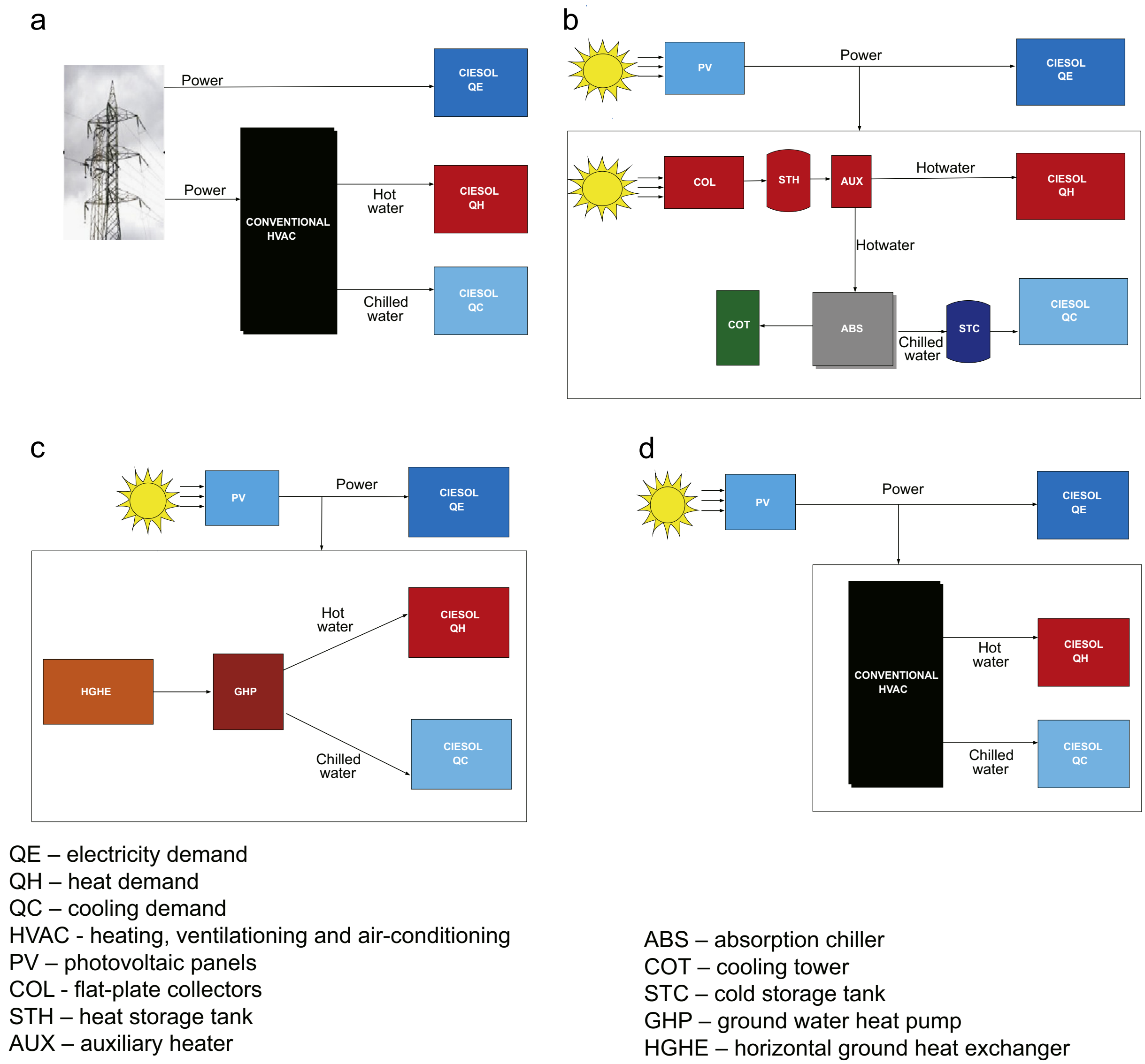

Fig. 25. Configurations of solar-assisted BCHP hybrid systems proposed for CIESOL building. (a) Design 1. (b) Design 2. (c) Design 3. (d) Design 4.

also the power usage registered in CIESOL building during 2011. As was already mentioned in Section 4.1 this consumption was of the order of 25.9 MWh/year (cf. Fig. 21(a)). Taking into account analysed values, for this design, we obtain the CIESOL's total power consumption of the order of 98 MWh/year. Nevertheless, the final design should also have the capability to handle additional demand changes. Thus, we need to consider at least 10% of total electric demand as a minimum surplus, to guarantee the value of the order of 108 MWh/year. This corresponds to a cost of 15.368 euro per year, considering a cost of electricity unit is 142.3 euro/MWh. As mentioned, we need to also include the annual maintenance cost, that represents 1% of investment (cf. Table 8) reaching 1200 euro per year, giving us the final annual running cost of 16.568 euro [14].

6.1.2. Design 2: solar absorption BCHP system

Fig. 25(b) illustrates the schematic diagram of Design 2. In this case the solar-assisted air-conditioning system, already introduced in Section 3.2, is used to provide heating and cooling demand. Meanwhile, entire CIESOL's electric requirement is covered by a photovoltaic system, that will be presented in details in the subsection below. Taking into account the annual electric energy consumption of the CIESOL building during 2011, (25.9 MWh/year, cf. Fig. 21(a)) and the total solar-assisted air-conditioning electricity usage (7.985 MWh/year, cf. Fig. 23(a)), we obtained the total power demand of the order of 33.88 MWh/year. As mentioned, the final design should also have the capability to handle additional demand, therefore we need to consider at least 10% of total electric expenditure as a minimum surplus, finally obtaining the value of the order of 37.5 MWh/year. Considering the data collected from the current photovoltaic installation, described in the Section 3.1, we calculated the required number of solar panels, that was of the order of 121. Given that each panel has an area of 1.628 m^2, the total area needed to place is 197 m^2. Using the total price of actual photovoltaic system, that is of the order of 40.000 euro, we calculated the final cost of the system consisting of 121 photovoltaic panels, that was of the order of 120.000 euro. The entire cooling and heating demands are met by solar-assisted air-conditioning system currently installed in CIESOL building. As mentioned, to produce chilled water in the desired temperature range, it is necessary to supply absorption chiller with hot water at a temperature between 70 °C and 95 °C, primarily from the array of solar collectors. When the solar hot water temperature is too low, the warm water from hot water storage tanks can be used. Otherwise, the auxiliary heater is used to drive the absorption

chiller. In Scenario 1 all produced energy is consumed internally in CIESOL building. As already stated, we compare each design to the reference system, therefore the cost of 15.368 euro per year presented for the Design 1 can be cancelled out, since the total electric demand in Design 2 is lower and can be entirely covered by photovoltaic system. To carry out the economic study, we need to consider all annual running costs, therefore we need to take into account also the natural gas consumption in the auxiliary heater, the deionised water consumption in the cooling tower and the annual maintenance cost. The natural gas consumption presented in Fig. 16(a) during 2011 was of the order of 229.5 m^3. Considering a unit cost of 0.36 euro/kWh we estimated the cost of natural gas equal to 86.5 euro/year. Another factor that we need to weigh up is the deionised water consumption produced in the cooling tower. After summer period of 2011 we found that this water consumption was of the order of 41.5 m^3 (cf. Fig. 16(b)), corresponding to 11.5 euro/year (unit cost of 0.28 euro/m^3). As suggested previously, we need also to consider the annual maintenance cost that represents 1% of investment (cf. Table 8) reaching 2.700 euro per year, giving us the final annual running cost of 2.798 euro [14]. The initial investment would be of order of 270.000 euro. Considering the fact that all produced energy will be autoconsumed, and comparing the presented design to the reference system (Design 1), we evaluated the payback period is 18.7 years. If we consider Scenario 2 the payback could decrease to 12.6 years. It is mainly due to the fact, that the annual return is higher than for the Scenario 1. This situation is caused by the income from self-production electricity. Bearing in mind the annual electricity production of the order of 37.5 MWh/year, and the Spanish legislation of the generation (from renewable sources) tariff is 0.32 euro/kWh, we calculated income of 12.000 euro/year. At the same time, the operating cost estimated for Scenario 2, corresponds to a cost of 5.336 euro per year, considering a cost of electricity unit at 142.3 euro/MWh. For this Scenario we assume the same annual maintenance, natural gas and deionised water cost as for Scenario 1. Therefore, the final annual running cost of Design 2 in Scenario 2 is of the order of 8.134 euro [14].

6.1.3. Design 3: solar geothermal electric compression BCHP system

Fig. 25(c) illustrates the schematic diagram of Design 3. This design consists of horizontal ground heat exchanger, hot water pump, heat pump, chilled water pump covering the air heating and cooling demand, and photovoltaic system to cover CIESOL's electric requirements. As was already described in Section 4.3, considering the total solar-assisted air-conditioning system's operation time of the order of 2769 h and the electric power of the heat pump and all peripheral equipments of the order of 28 kW, we can estimate heat pump's annual power consumption of 77.5 MWh. As in the above case, we take into account the power consumption of CIESOL's building, that was of the order of 25.9 MWh/year (cf. Fig. 21(a)). Taking into account both analysed consumptions, for this design, we obtain the CIESOL's total power consumption of the order of 103.4 MWh/year. However, as in the above case, considering 10% of the possible changes, the final electric demand will be of the order of 113.8 MWh/year. Considering the data gathered from the current photovoltaic installation, described in the Section 3.1, we calculated the required number of solar panels was of the order of 366. Given that each panel has an area of 1.628 m^2, the total area needed to place of all the photovoltaic panels is 596 m^2. Using the total price of actual photovoltaic system, that was of the order of 40.000 euro, we calculated the final cost of the system, consisting of 366 photovoltaic panels, was found to be 349.000 euro. As mentioned, we compare each design to the reference system, therefore the cost of 15.368 euro per year presented for the Design 1 can be cancelled out, since the total electric demand in Design 3 will be entirely covered by photovoltaic system. To carry out the economic study, we need to consider all annual running costs, as well the annual maintenance cost, that represents 1% of investment (cf. Table 8) reaching 4.050 euro per year, giving us the final annual running cost of 4.050 euro. The initial investment would be of order of 405.000 euro. Allowing for the fact that all produced energy is be autoconsumed, and comparing the presented design to the reference system (Design 1), we evaluated the payback period in 31.5 years. If we consider Scenario 2 the payback could decrease to 12 years. This is caused by the fact that the annual return is higher than for the Scenario 1. This situation is a consequence of the incomes from self-production electricity. Considering the annual electricity production of the order of 113.8 MWh/year and the Spanish legislation of the generation (from renewable sources) tariff which is 0.32 euro/kWh, we calculated income of 36.408 euro/year. At the same time, the operating cost estimated for Scenario 2, corresponds to a cost of 16.190 per year, assuming cost of electricity unit at 142.3 euro/MWh. For this Scenario we adopt the same annual maintenance cost as for Scenario 1. Therefore, the final annual running cost of Design 3 in Scenario 2 is of the order of 20.240 euro.

6.1.4. Design 4: solar electric compression BCHP system

Fig. 25(d) illustrates the schematic diagram of Design 4. This design consists of photovoltaic system to cover CIESOL's electric demand and conventional HVAC system to cover heating and cooling demand of CIESOL building. The total electric demand for this design was calculated in the same way, as for the reference system, obtaining the final value of the order of 108 MWh/year. In view of the data obtained from the current photovoltaic installation, described in the Section 3.1, we calculated the required number of solar panels, that was of the order of 347. Taking into account, that each panel has an area of 1.628 m^2, the total area needed to place of all the photovoltaic panels is 565 m^2. Using the total price of actual photovoltaic system, that was of the order of 40.000 euro, we calculated the final cost of the system consisting of 347 photovoltaic panels, was 330.000 euro. As before, we compare each design to the reference system, therefore the cost of 15.368 euro per year presented for the Design 1 can be cancelled out, since the total electric demand in Design 4 is entirely covered by photovoltaic system. To carry out the economic study, we need to consider all annual running costs, as well the annual maintenance cost, that represents 1% of investment reaching 3.420 euro per year, giving us the final annual running cost of 3.420 euro. The initial investment would be of order of 342.000 euro. Bearing in mind that all produced energy will be autoconsumed and comparing the presented design to the reference system (Design 1), we evaluated that the payback period is 25 years. If we consider Scenario 2 the payback could decrease to 10 years. The reason for that payback decrease is the fact that annual return is higher than in the Scenario 1. This situation is caused by the incomes from self-production electricity. Knowing that the annual electricity production is of the order of 108 MWh/year, and the Spanish legislation of the generation (from renewable sources) tariff is 0.32 euro/kWh, we calculated incomes in 34.560 euro/year. At the same time, the operating cost estimated for Scenario 2, corresponds to a cost of 15.368 euro per year, totaling in cost of electricity unit at 142.3 euro/MWh. For this Scenario we consider the same annual maintenance cost as for Scenario 1. Therefore, the final annual running cost of Design 4 in Scenario 2 is of the order of 18.788 euro.

6.2. Comparative results

Table 7 presents the general data and energy performance of three solar-assisted hybrid BCHP systems proposed for CIESOL

Table 7
Result summary of the design alternatives: technical features.

Energy-related comparison	Unit	Reference system	Design 2	Design 3	Design 4
General data					
Photovoltaic panels	(m^2)	–	197	596	565
Flat-plate collectors	(m^2)	–	160	–	–
Ground heat exchanger	(m^2)	–	–	370	–
Volume of heat storage	(m^3)	–	10	–	–
Auxiliary heater	(kW)	–	100	–	–
Cooling capacity, absorption chiller	(kW)	–	70	–	–
Cooling capacity, cooling tower	(kW)	–	170	–	–
Volume of cold storage	(m^3)	–	5	–	–
Cooling capacity, geothermal heat pump	(kW)	–	–	62	–
Cooling capacity, compression chiller	(kW)	76.4	–	–	76.4
Production					
Annual electricity production	(MWh/y)	–	37.5	113.8	108
Annual cold production	(MWh/y)	14.5	14.5	14.5	14.5
Annual heat production	(MWh/y)	10.31	10.31	10.31	10.31
Annual radiation on collectors and pv panels	(kWh/m^2)	–	1650	1650	1650
Consumption					
Annual electricity consumption (including pumps, control, etc.)	(MWh/y)	108	37.5	113.8	108
Annual deionised water consumption	(m^3/y)	–	41	–	–
Annual natural gas consumption	(m^3/y)	–	229.5	–	–
Annual heat from second heat source	(MWh)	–	9.73	–	–
Annual amount of fossil heat source (primary energy)	(MWh)	–	10.41	–	–
Maximum electricity demand (maximum hourly value)	(kW)	47.7	32.34	49.1	47.7
Savings					
Annual primary energy consumption	(MWh/y)	227.88	89.53	240.06	227.88
Annual primary energy savings	(MWh/y)	–	138.34	−12.18	–
Relative primary energy savings	(%)	–	61	–	–

Table 8
Result summary of the design alternatives: economical aspects Scenario 1.

Cost element	Unit	Reference system	Design 2	Design 3	Design 4
Initial cost					
Photovoltaic panels (including supporting structure and installation)	(€)	–	120.000	349.000	330.000
Solar collectors cost (including supporting structure and installation)	(€)	–	50.000	–	–
Heat storage units	(€)	–	7.500	–	–
Auxiliary heater	(€)	–	2.500	–	–
Compression chiller	(€)	8.000	–	–	8.000
Absorption chiller	(€)	–	55.000	–	–
Geothermal heat pump	(€)	–	–	15.000	–
Ground heat exchanger pipes	(€)	–	–	12.000	–
Cooling tower	(€)	–	6.000	–	–
Cold storage units	(€)	–	5.500	–	–
Pumps, pipes	(€)	1.000	10.000	6.000	1.000
Monitoring and control system	(€)	2.000	8.000	3.000	2.000
Installation costs	(€)	1.000	5.500	20.000	1.000
Final total investment cost (without funding subsidies)	(€)	**12.000**	**270.000**	**405.000**	**342.000**
Scenario 1					
Annual running costs					
Annual electricity cost (consumption)	(€/y)	15.368	–	–	–
Annual natural gas cost	(€/y)	–	86.5	–	–
Annual deionised water cost	(€/y)	–	11.5	–	–
Maintenance	(€/y)	1.200	2.700	4.050	3.420
Final operation and maintenance cost	(€/y)	**16.568**	**2.798**	**4.050**	**3.420**
Annual savings					
Electricity production	(MWh/y)	–	37.5	113.8	108
Electricity self-production	(k €/MWh)	–	–	–	–
Electricity self-production	(k €/y)	–	–	–	–
Comparative evaluation					
Annual return	(€/y)	–	−2.798	−4.050	−3.420
Payback period	**(y)**	**Never**	**18.7**	**31.5**	**25**

building as an alternative to the conventional BCHP system. The first part of the Table 7 contains data on the dimensions of described configuration systems' components such as the solar collectors, photovoltaic panels, water storage tanks, absorption chiller, etc. Two following parts of this table demonstrate the annual energy balance of all proposed designs. The final part illustrates the primary energy saving, since we believe that it is the key parameter allowing the comparison of any hybrid system with conventional reference system [2]. As we can see, only the adoption of second design involves primary energy savings of

Table 9
Result summary of the design alternatives: economical aspects Scenario 2.

Cost element	Unit	Reference system	Design 2	Design 3	Design 4
Initial cost					
Photovoltaic panels (including supporting structure and installation)	(€)	–	120.000	349.000	330.000
Solar collectors cost (including supporting structure and installation)	(€)	–	50.000	–	–
Heat storage units	(€)	–	7.500	–	–
Auxiliary heater	(€)	–	2.500	–	–
Compression chiller	(€)	8.000	–	–	8.000
Absorption chiller	(€)	–	55.000	–	–
Geothermal heat pump	(€)	–	–	15.000	–
Ground heat exchanger pipes	(€)	–	–	12.000	–
Cooling tower	(€)	–	6.000	–	–
Cold storage units	(€)	–	5.500	–	–
Pumps, pipes	(€)	1.000	10.000	6.000	1.000
Monitoring and control system	(€)	2.000	8.000	3.000	2.000
Installation costs	(€)	1.000	5.500	20.000	1.000
Final total investment cost (without funding subsidies)	(€)	**12.000**	**270.000**	**405.000**	**342.000**
Scenario 2					
Annual running costs					
Annual electricity cost (consumption)	(€/y)	15.368	5.336	16.190	15.368
Annual natural gas cost	(€/y)	–	86.5	–	–
Annual deionised water cost	(€/y)	–	11.5	–	–
Maintenance	(€/y)	1.200	2.700	4.050	3.420
Final operation and maintenance cost	(€/y)	**16.568**	**8.134**	**20.240**	**18.788**
Annual savings					
Electricity production	(MWh/y)	–	37.5	113.8	108
Electricity self-production	(k €/MWh)	–	320	320	320
Electricity self-production	(k €/y)	–	**12.000**	**36.408**	**34.560**
Comparative evaluation					
Annual return	(€/y)	–	3.865	16.168	15.772
Payback period	(**y**)	**Never**	**12.6**	**12**	**10**

Table 10
Result summary of the designed alternatives: environmental performance.

Element	Unit	Reference system	Design 2	Design 3	Design 4
Environmental issues					
Saved primary energy	(MWh)	–	138.34	–\`	–
CO_2 saving due to primary energy savings	(kg)	–	34,585.0	–	–
CO_2 saving due to heat saving	(kg)	–	−2099.7	–	–
Water saving	(m^3)	–	-41	–	–
Total CO_2 saving	(**kg**)	–	**32,485.3**	–	–
Refrigerant type		R-410a,32,125	H_2O	R-410a,32,125	R-410a,32,125
Environmental advantage		Non ozone-depleting	Environmental friendly refrigerant	Non ozone-depleting	Non ozone-depleting
Environmental disadvantage		Powerful greenhouse effect	–	Powerful greenhouse effect	Powerful greenhouse effect

about 138 MWh per year, that means that solar absorption BCHP system makes it possible to save approximately 61% of the total electrical energy that would otherwise be consumed by conventional system. The feasibility of each option was assessed in terms of its primary energy savings, initial cost, operating cost, maintenance cost, avoided costs and payback period in two earlier introduced scenarios. Tables 8 and 9 summarise the main results obtained for Scenario 1 and Scenario 2, respectively. It has to be emphasised that in three studied solar-assisted hybrid BCHP systems, the initial investment cost of these devices still represents an insurmountable economic barrier (high payback period), which is in accordance with benefits realisation reported by Bizzarri and Morini [12].

Topic of the last part of this study is an applied environment assessment of three studied alternatives for meeting CIESOL's electric and air-conditioning requirements. We compared those alternatives with the conventional system. Table 10 presents the primary energy savings and reduction of CO_2 emissions to the atmosphere for four presented solar-assisted hybrid BCHP systems designs. As can be seen, only the second design involves the primary energy and CO_2 savings. As shown earlier, during operation, the solar-assisted BCHP system needs deionised water to supply the cooling tower. Alternatively, natural gas is burned in the auxiliary heater if the water from the solar collectors' array outlet does not reach the required temperature. The electricity for the building and for absorption chiller, pumps, etc. is supplied by the photovoltaic modules. Concerning the conventional BCHP system, electricity from the grid is the only input needed during operation. It was calculated that applying Design 2 we are able to reduce total primary energy expenditure of about 138.34 MWh/year, that results in CO_2 reduction. The total CO_2 savings are estimated considering the CO_2 emissions due to primary energy savings and consumption of natural gas for heat production in auxiliary heater. In this study, we used the general CO_2 emission rate for production of conventional electricity of the order of 250 g/kWh and the CO_2 emission rate for the natural gas

consumption of the order of 201.7 g/kWh [44]. The solar-assisted BCHP system involves CO_2 savings of 32.5 tons per year, which represents the emissions of almost four Spanish persons in the equivalent years (9.6 tons CO_2 person/year) [24]. We would like to draw attention to the advantages of using H_2O as environmental friendly refrigerant. The reference system uses the following refrigerants: R-410a, a near-azeotropic mixture of difluoromethane (CH2F2, called R-32) and pentafluoroethane (C2HF5, called R-125). These refrigerants are non ozone-depleting, although they are powerful greenhouse gases.

6.3. Conlusions

In this study, three solar-assisted hybrid BCHP systems were described as alternatives to a conventional BCHP system for the existent office building located in Almería (southern Spain). The solar-assisted hybrid BCHP systems included the solar absorption BCHP system (Design 2), solar geothermal electric compression BCHP system (Design 3) and solar electric compression BCHP system (Design 4). We used the primary energy and CO_2 savings, initial cost, operating cost, maintenance cost, avoided costs and payback period as key performance indicators. The energy performance of solar-assisted hybrid BCHP systems has been estimated, by benchmarking entire energy infrastructure operating today in the CIESOL building, to find the more favourable BCHP system with regards to energy lifecycle and environmental point of view. The results achieved demonstrated that only the solar absorption BCHP system presents energy saving potential. Adopting a new eco-design and a solar absorption BCHP system in the CIESOL building realised a large energy saving potential. At the same time, we used solar resource, abundant in the Almería region, in an efficient way, making CIESOL building consumption less energy intensive and ensuring environmental protection. It was shown that, during 1 year, the solar absorption BCHP system uses 61% less primary energy than the conventional BCHP system. In addition, the solar absorption BCHP system requires less space comparing to the Designs 3 and 4, where more than 596 m^2 and 565 m^2 of photovoltaic panels are needed. Moreover, when we consider the initial and annual running cost of this scenario, the designed off-grid system is able to cover entire cooling, heating and power CIESOL's demand. It certainly appears to be worth investing in. This is because among all studied solar-assisted hybrid BCHP systems it presents the smallest initial investment and its annual operation cost is smaller than of other hybrid systems: its estimated payback period is 18.7 years. However, the results obtained for Scenario 2, where the produced electricity is sold back to the grid and the CIESOL's electricity demand is covered by external campus' grid, have shown that the solar geothermal electric compression BCHP system starts generating profits just after 10 years. The drawback here is that it does not present any primary energy or CO_2 savings. We conclude that it is possible to cover the building's cooling, heating and power demands with the sustainable technology designs. Those allow us to substantially reduce fossil energy demand and greenhouse gas emissions, using commercially available equipment. Nevertheless, solar absorption BCHP system is still in early stages of development and efforts must be made to improve its performance not only in terms of economic competitiveness but also in environmental terms. Future efforts should be also channeled into evaluating all three hybrid BCHP systems by means of life cycle assessment, and into comparing them to the conventional system. This evaluation needs to include all stages of design and operation of those systems. We suggest to carry out further research on replacing the solar collectors and photovoltaic installation with a micro cogeneration device as a part of continuous improvement in environmental sustainability. We are also encouraged by recent findings [24] that confirmed the main infrastructure contributors of the solar-assisted air-conditioning system. Recently, cogeneration became popular as a very competitive method for simultaneous power and heat production from the single source, especially applicable to the construction industry. The heat produced can be used for heating during winter time and additionally could be used to supply absorption chiller in summer period, providing in parallel electricity to the building or injecting it to the grid.

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